DECAY AND PRODUCTION OF FLUX–TUBE EXCITATIONS IN MESONS

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The organization is as follows. We start by developing flux–tube decay and production dynamics in an *a priori* fashion, and then briefly indicate its foundation in QCD. We then specialize to the flux–tube model and indicate various selection rules. We proceed to highlight the experimental candidates and their signatures at current and future facilities.

FLUX–TUBE DYNAMICS

The chromo-electric flux–lines eminating from a coloured quark and absorbed by a neighbouring antiquark is known to confine the system. This is not achievable when flux–lines spread out equally in space around a single charge, as is the case in classical electromagnetism. The opposite extreme where the flux-lines between the quark and antiquark are compactified into a *flux–tube*, however, means that the attraction force is constant as the interquark distance is traversed, and the energy of dissociation hence infinite : exactly what we need for the experimental datum of *confinement.* We hence adopt the idea of a chromo-electric flux–tube connecting a quark and antiquark.

Having understood that *mesons* can be regarded as $Q\bar{Q}$ systems connected by a flux–tube, it is natural to consider quantum *excitations* of these systems, which we shall call *hybrids.*

In order to simplify the discussion as a first orientation we would like to conceptually seperate the dynamics of the "quark" and "flux" components of the system. This is called the *adiabaticity* assumption, and is valid for large quark masses. As the quarks move, the flux–tube is considered to spontaneously re-assemble itself; and hybrids are $Q\bar{Q}$ systems with an excited flux–tube. There would in principle be an infinite tower of excitations, but we shall specialize to the energetically lowest lying one in this lecture. The flux–tube can possess angular momentum Λ around the $Q\bar{Q}$–axis $\mathbf{r}_A$, which is conserved as the flux–tube must *a priori* be invariant under rotations around the $Q\bar{Q}$–axis. This system hence has *three* quantum numbers : the usual angular momentum L with its projection M *as well as* Λ. The only mathematical function of the direction variables θ, ϕ defining the direction of the $Q\bar{Q}$–axis, which is an eigenfunction of the above three conserved operators, is the Wigner rotation function $\mathcal{D}^L_{M\Lambda}$. It then accordingly gives the angular dependence of the wave function of the system. The quarks move adiabatically in an effective potential generated by the flux–tube dynamics, and hence obeys a Schrödinger equation which determines the dependence on $Q\bar{Q}$ seperation of the wave function of the system.

We now consider how these systems might decay. For a two–body decay it would be natural to assume the creation of a $q\bar{q}$ pair. If we constrain ourselves to a *local* theory, the $q\bar{q}$ pair must be created at *one* point $\mathbf{y}$ (see figure 1). This point is also called the point of "flux–tube breaking" because a very thin tube of flux for the incoming state A would "break" into two similar flux–tubes for the outgoing states B and C. In general, however, the flux–tube would be expected to have a definite *thickness*. According to the adiabaticity assumption, the initial flux–tube would have to re–assemble into the flux–tubes of the two final states. This would have a certain re–arrangement amplitude, which we call the *flux–tube overlap* $\gamma(\mathbf{r}_A, \mathbf{y})$.

The $q\bar{q}$ pair creation operator is naïvely not expected to add angular momentum to the system, since we would expect it to be rotationally invariant and derivable from a Lorentz invariant operator. Thus $J_{q\bar{q}} = 0$. The simplest such operator is $\bar{\psi}\psi = \psi^+\gamma_0\psi$ which can be expanded to give an operator of the form $\boldsymbol{\sigma} \cdot \mathbf{p}$, noting that γ_0 is off–diagonal and $\boldsymbol{\sigma}$ are Pauli matrices. Here the $q\bar{q}$ pair has spin $S_{q\bar{q}} = 1$ (due to $\boldsymbol{\sigma}$) and orbital angular momentum $L_{q\bar{q}} = 1$ (due to $\mathbf{p}$). The decay process is hence called "$^3P_0$ pair creation". Here $\vec{J}_{q\bar{q}} = \vec{S}_{q\bar{q}} + \vec{L}_{q\bar{q}}$; and we use the condensed notation $^{2S+1}L_J$.

$^3P_0$ pair creation can arize from the strong coupling expansion of the Hamiltonian formulation of lattice gauge theory [1] or from the instantaneous colour Coulomb interaction [2] and is phenomenologically surprisingly successful [3]. We adopt it.

By the conservation of spin (since the decay operator creates a $S_{q\bar{q}} = 1$ pair) we obtain the following selection rule :

(A) Decays of net spin $S = 0$ states to two $S = 0$ states are forbidden.

The $^3P_0$ decay amplitude can be formulated most intuitively in the momentum frame with the $q\bar{q}$–pair being created with equal but opposite momenta $\mathbf{k}_3, \mathbf{k}_4$ as

$$\int d^3\mathbf{k}_1\, d^3\mathbf{k}_2\, d^3\mathbf{k}_3\, d^3\mathbf{k}_4\, \delta^3(\mathbf{k}_1+\mathbf{k}_2-\mathbf{p}_A)\, \delta^3(\mathbf{k}_1+\mathbf{k}_3-\mathbf{p}_B)\, \delta^3(\mathbf{k}_2+\mathbf{k}_4-\mathbf{p}_C)\, \delta^3(\mathbf{k}_3+\mathbf{k}_4)$$
$$\times\, \boldsymbol{\sigma}\cdot(\mathbf{k}_3-\mathbf{k}_4)\, \psi_A(\frac{\mathbf{k}_2-\mathbf{k}_1}{2})\, \psi_B^*(\frac{\mathbf{k}_3-\mathbf{k}_1}{2})\, \psi_C^*(\frac{\mathbf{k}_2-\mathbf{k}_4}{2}) \qquad (1)$$

where $\mathbf{k}_1, \mathbf{k}_2$ represent the momenta of the incoming quarks and care has been taken to constrain the constituent momenta $\mathbf{k}_i$ to equal the meson momenta $\mathbf{p}_{A,B,C}$. The factor $\mathbf{p} = \mathbf{k}_3 - \mathbf{k}_4$ is the relative momentum of the $q\bar{q}$ pair. The expression in Eq. 1 can be shown by change of variables [4],[5][Appendix A.1] to equal (for a flux–tube overlap $\gamma(\mathbf{r}_A, \mathbf{y}) = 1$)

$$(2\pi)^3\delta^3(\mathbf{p}_B+\mathbf{p}_C) \int d^3\mathbf{r}_A\, d^3\mathbf{y}\, \psi_A(\mathbf{r}_A) \exp(\frac{i}{2}\mathbf{p}_B\cdot\mathbf{r}_A)\, \gamma(\mathbf{r}_A,\mathbf{y})$$
$$\times\, \boldsymbol{\sigma}\cdot(2i\boldsymbol{\nabla}_{\mathbf{r}_A}+\mathbf{p}_B)\, \psi_B^*(\frac{\mathbf{r}_A}{2}+\mathbf{y})\psi_C^*(\frac{\mathbf{r}_A}{2}-\mathbf{y}) \qquad (2)$$

Figure 1: The topology of flux–tube decay and production

in position space, where we defined the Fourier transformed wave functions $\psi_{A,B,C}(\mathbf{r}) = (2\pi)^{-3} \int d^3\mathbf{k}\, \exp(i\mathbf{k}\cdot\mathbf{r})\psi_{A,B,C}(\mathbf{k})$; and restricted $\mathbf{p}_A = 0$. We shall now generalize to an arbitrary function $\gamma(\mathbf{r}_A, \mathbf{y})$.

We have thus discussed the generic formulation of decay dynamics in an adiabatic and non–relativistic context with $^3P_0$ pair creation. For more information on the flux–tube overlap we specialize to a specific model.

THE FLUX–TUBE MODEL

A detailed form of the flux–tube overlap has successfully been obtained in the Isgur-Paton non–relativistic flux–tube model of QCD [6], which is almost the *only* non–perturbative context in which decays and production of flux–tube excitations have been discussed in the literature. We shall briefly state two important properties without deriving them.

1. For *meson decays to two mesons* the overlap reduces to a constant for infinitely thick flux–tubes, yielding the old and phenomenologically successful [3] $^3P_0$–model amplitude of Eq. 1. Flux–tube model predictions with flux–tubes of finite thickness differ insignificantly [1, 5] from the $^3P_0$–model, effectively disguising the presence of the flux–tube : thus explaining the success of quark–model ideas for conventional mesons.

2. For *hybrid decays to two mesons* the overlap is odd under the transformation $\mathbf{y} \to -\mathbf{y}$, and hence pair creation on the incoming $Q\bar{Q}$–axis is *forbidden.*

The second property has important experimental consequences. If the final states are identical S–wave states, the wave functions carry no angular momentum indices and are thus equal : $\psi_B = \psi_C$. The function in Eq. 2 inside the integral is then odd under $\mathbf{y} \to -\mathbf{y}$ (due to the oddness of $\gamma(\mathbf{r}_A, \mathbf{y})$), yielding a vanishing decay amplitude on $\mathbf{y}$–integration. Thus the decay amplitude is proportional to the difference of the wave functions of the outgoing mesons. This difference is usually small [7] leading to a selection rule :

(B) Decays of hybrids to two S–wave mesons are suppressed.

This selection rule can heuristically be understood as follows. Heavy quark lattice gauge theory (HQLGT) [8] suggests that the lowest lying hybrids have $\Lambda = 1$, while mesons have $\Lambda = 0$. There is thus no available angular momentum amongst the outgoing mesons to absorb the $\Lambda = 1$ of the incoming hybrid.

Rule B has the immediate corollary

(C) Decays to one $L = 1$ and one $L = 0$ meson are the preferred decay channel for hybrids.

This is due to significant amounts of phase space often available and easier detection relative to even higher L final states.

In the case of *production*, where an exchanged π, ρ or ω is involved, it is possible that the strength of production could be significant at least to the extent that the exchanged off mass-shell state may have different structure to the incident on-shell beam particle. This is because rule B is invalidated, making this method of production important. Hence :

(D) Meson exchange can be a significant production mechanism for hybrid mesons.

A specific example is the *photoproduction* of hybrids where the interaction $\gamma + meson \to hybrid$ offers unique opportunities. The photon γ can be regarded as a linear combination of ρ, ω, ϕ mesons (with $J^{PC} = 1^{--}$) by vector meson dominance. The photon can be produced directly or in e^+e^-–annihilation.

To complete the discussion of the flux–tube model, we mention the J^{PC} quantum numbers of the *lowest lying* hybrid mesons, which are the same as in HQLGT [8]. They may be divided into two classes :

(a) $0^{-+}, 1^{+-}, 1^{--}, 1^{++}, 2^{-+}$ (deemed "conventional" in that they can also be shared by standard $q\bar{q}$ states), and

(b) $0^{+-}, 1^{-+}, 2^{+-}$ (deemed "exotic").

In the hybrid 1^{--} and 1^{++}, $S = 0$; all other J^{PC} have $S = 1$.

THE HYBRID HUNTER'S GUIDE

A central theme in this section will be to apply the preceding rules to a case study. We shall see that even when hybrid and conventional mesons have the *same* J^{PC} quantum numbers, they may be distinguished. The essential reason is that although superficially identical in their overall quantum numbers, the two states have different internal structures. We illustrate this with particular reference to the vector meson "$\rho_1(1460)$" [9], usually denoted as $\rho(1450)$, whose decays typify those of 1^{--} hybrid dynamics, making it a strong hybrid candidate.

(i) For $J^{PC} = 1^{--}$, rule A distinguishes between conventional vector mesons which are $^3S_1$ or $^3D_1$ states and hybrid vector mesons where the $q\bar{q}$ have $S_{q\bar{q}} = 0$. This implies that in the decays of hybrid ρ, the channel πh_1 is forbidden whereas πa_1 is allowed and that πb_1 is analogously suppressed for hybrid ω decays; this is quite opposite to the case of $^3L_1$ conventional mesons where the πa_1 channel is relatively suppressed and πh_1 or πb_1 are allowed [1]. The extensive analysis of data in Ref. [9] revealed the clear presence of $\rho(1450)$ with a strong πa_1 mode but no sign of πh_1, in accord with the hybrid hypothesis.

(ii) Applying rules B and C, we observe that in decays of hybrid $\rho \to 4\pi$ the πa_1 content is predicted to be dominant and the $\rho\rho$ to be absent. The analysis of Ref. [9] again finds such a pattern for $\rho(1450)$.

(iii) Rule B no longer operates if the internal structure or size of the two $L = 0$ states differ, as noted before. Thus, for example, decays to $\pi + \rho$, $\pi + \omega$ or $K + K^*$ may be significant in some cases [7]. Though still suppressed relative to the dominant pathway, (ii) above, this too is the case for $\rho(1450)$.

(iv) Couplings to $\rho\omega$ or $\rho\pi$ could be considerable when the ρ is effectively replaced by a photon and the ω or π is exchanged in photoproduction, illustrating rule D. We hence would advocate searching for the lightest 1^{--} hybrids in diffractive photoproduction : $\gamma(p) \to \pi a_1(p) \to 4\pi(p)$.

LIGHT HYBRID CANDIDATES

$\underline{1^{--}}$

Continuing the previous section, we predict [7] for a vector hybrid $\rho(1450)$ the widths (in MeV)

$$\pi a_1 : \pi a_2 : \pi h_1 : \rho\rho : \pi\omega : \pi\pi \;=\; 140 : \sim 0 : 0 : 0 : 5 - 10 : 0 \qquad (3)$$

These are very different from the predictions of radial or $^3D_1$ decays of quarkonia [1]. In particular the suppression of πh_1 relative to πa_1 alluded to in the previous section, is a crucial test of the hybrid initial state. It is therefore interesting that the detailed analyses of experimental data in Ref. [9] comment on the apparently anomalous decays that they find for the 1^{--} state $\rho(1450)$, in particular the suppression of πh_1 relative to πa_1 and the dominance of the latter over the $\pi\omega$:

$$\pi a_1 : \pi h_1 + \rho\rho : \pi\omega : \pi\pi \;=\; 190 : 0 - 39 : 50 - 80 : 17 - 25 \qquad (4)$$

It is noticeable that the $\pi\pi$ decay also is strongly suppressed though non–zero; if this is substantiated it could indicate either a deviation from the flux–tube model or in addition some mixing between hybrid and radial 1^{--} mesons in this region. The latter could also rather naturally explain the enhancement of the $\pi\omega$ channel as well as the repulsion of the eigenstate to low mass.

Ref. [9] also finds evidence for $\omega(1440)$ with no visible decays into πb_1 which is in significant contrast to the expectations for conventional $Q\bar{Q}$ ($^3S_1$ or $^3D_1$) initial states. In the hybrid interpretation this suppression is natural and is the isoscalar analogue of the πh_1 selection rule alluded to above.

If the $\rho(1450)$ has signposted the existence of the 1^{--} hybrid nonet, then we need to establish which of the other seven multiplets should also be visible. States whose couplings are predicted to be strong, with highly visible decay channels and moderate widths relative to the $\rho(1450)$ candidate, *must* be seen if hybrids are to be established. Conversely, channels where no signals are seen should be those whose signals are predicted by the flux–tube model to be weak. These criteria *do* appear to be realised in the data, as shall now be discussed.

For conventional J^{PC} hybrids at $\sim$ 2 GeV made from u, d flavoured quarks the $1^{+-}, 1^{++}$ states are over 500 MeV wide [7] in both I=0,1 states; by contrast the $0^{-+}, 2^{-+}$ and the 1^{--} are predicted to be potentially accessible. We now discuss the former two states.

$\underline{0^{-+}}$

The VES Collaboration sees an enigmatic and clear 0^{-+} signal in diffractive π production [10]. They study the channels $\pi^- N \to \pi^-\pi^+\pi^- N$; $\pi^- K^+ K^- N$; $\omega\pi^-\pi^0 N$; $\eta\eta\pi^- N$ and see a resonant signal of mass 1770 MeV and width 190 MeV in the classic $(L = 0) + (L = 1)$ $\bar{Q}q$ channels $\pi^- + f_0(1400)$; $K^- + K_0^*$ with no corresponding strong signal in the allowed $L = 0$ two body channels $\pi + \rho$; $K + K^*$. The width and large couplings to kaons (in the dominant [10] decay channels $f_0(980)\pi^-$ and $a_0^-\eta$) are both surprising if this were the second radial excitation of the pion (the first radial excitation is seen as a broad enhancement in accord with expectations). Furthermore, the apparent preference for decay into $(L = 0) + (L = 1)$ mesons at the expense of $L = 0$ pairs is qualitatively in accord with expectations for hybrids.

Our quantitative estimates [7] on the relative importance of available channels further suppport this identification. We find widths to $\pi f_0(1300)$ of $\sim$ 170 MeV and to πf_2 of $5 - 10$ MeV. The KK_0^* channel is kinematically suppressed though probably non–zero due to the $\sim$ 300 MeV width of the $K_0^*(1430)$. The decay to $L = 0$ pairs, which is naively expected to be suppressed, turns out to be potentially significant, $\pi\rho \sim 30$ MeV. This is compatible with the experimental limit [10]

$$\frac{0^{-+} \to \pi^-\rho^0}{0^{-+} \to \pi^- f_0(1300)} \ < \ 0.07 \tag{5}$$

The $KK^*(890)$ channel, by contrast, is expected to be a mere $\sim$ 5 MeV, which is consistent with the observed order of magnitude suppression observed in Ref. [10]

$$\frac{0^{-+} \to K^-K^*}{0^{-+} \to (K^-K^+\pi)_S} \ < \ 0.1 \tag{6}$$

In addition it is found [7] that the total width is in accordance with expectations. Important tests are now that there should be a measureable coupling to the $\pi\rho$ channel with only a small πf_2 or KK^* contribution.

Of special interest is the observation of decays into $f_0(1500)\pi$, since $f_0(1500)$ is a strong glueball candidate. If sustained, this would indicate the presence of a "gluon–rich" decay mode.

The 0^{-+} may be prominent in low energy photoproduction where π exchange is important but its $\omega\gamma$ coupling is suppressed by a selection rule [7] for hybrids which will disfavour the 0^{-+} photoproduction at higher energies where ω–exchange is more dominant.

$\underline{2^{-+}}$

The prediction [7] for the 2^{-+} VES partner to the 0^{-+} is that the πf_2 channel should dominate significantly over the πf_0 channel. This is a problem if one wishes to identify the isovector 2^{-+} seen at ~ 2.2 GeV at VES as the hybrid partner of the 0^{-+}. The putative signal is claimed in $\pi f_0(1300)$ whereas no πf_2 nor $\pi f_0(980)$ are reported. The properties and existence of this state are less clearcut experimentally. If $\pi f_0(1300) \geq \pi f_2(1270)$ is sustained for this state, it is not a hybrid.

Historically the ACCMOR Collaboration [11] noted a 2^{-+} structure around 1.8 GeV, coupled to πf_2, and too near to the $\pi_2(1670)$ for these to be the 1^1D_2 and 2^1D_2 (radial excitation) of conventional quarkonium. This structure is tantalisingly similar to sightings of a possible 2^{-+} (or even 1^{-+}) at 1.77 GeV, width 100-200 MeV in photoproduction via π exchange [12] and coupled to $\pi\rho$ and πf_2. An earlier low energy photoproduction experiment [13] also shows a clear structure at 1.7 - 1.9 GeV though its quantum numbers are not identified; we note that hybrid $2^{-+}, 1^{-+}$ are both favourably photoproduced [7] *via* π exchange or ω exchange. If these various experiments are heralding activity in the 2^{-+} isovector wave, a search for the πb_1 decay channel becomes pivotal. This follows once again from rule A : this prevents the decay of ${}^1D_2(\pi_2) \to b_1\pi$ whereas this channel is allowed and potentially significant for a hybrid π_2 [7].

There are also indications of a doubling of states in the $I = 0$ $\eta\pi^0\pi^0$ channel where the Crystal Barrel at LEAR [14] finds both $\eta_2(1645)$ (which is probably the partner of $\pi_2(1650)$) and also a candidate $\eta_2(1875)$ decaying into $f_2\eta$ but not $a_2\pi$ (unlikely to be $s\bar{s}$). Our calculation [4, 7] predicts the widths (in MeV)

$$\pi a_2 : \eta f_2 : K^*K \;=\; 160 : \sim 20 : 1 \tag{7}$$

so that the total width is consistent with the 200 MeV observed; but the πa_2 channel should now be sought.

$\underline{1^{-+}}$

The most obvious signature for a hybrid meson is the appearance of a isospin 1 state with an exotic combination for J^{PC}. It was noted in Ref. [15] and confirmed in Ref. [7] that the 0^{+-} width is predicted to be over 1500 MeV thereby rendering the state effectively invisible. The 2^{+-} is also predicted to be very broad and hard to see if its mass is ≥ 1.9 GeV. The best opportunity for isolating exotic hybrids appears to be in the 1^{-+} wave where the AGS at Brookhaven [16] may have indications for such an isospin 1 state whose mass and decay characteristics are in line with expectations. The search was motivated by rule C and concentrated on the decay channel $\pi + f_1$, which is where the candidate has been sighted. The experiment sees a broad structure in the mass region $1.6 - 2.2$ GeV which is suggestive of being a composite of two objects at 1.7 and 2.0 GeV. It is the latter that appears to have a resonant phase. The current data suffers from low statistics, making its existence in need of independent corroboration.

Our expectations [7] for widths are (in MeV)

$$\begin{aligned} \pi f_1 : \pi b_1 : \eta a_1 : \pi\eta(1295) &= 60 : 170 : 30 : 30 \\ \pi\rho : \eta\pi : \eta'\pi : \rho\eta &= 5-20 : 0-10 : 0-10 : 0-10 \end{aligned} \tag{8}$$

We note the possible presence of $\pi\rho$ or even $\pi\eta$ decays that are not negligible relative to the signal channel πf_1, due to significant final state wave funtion differences softening rule B. This may be important in view of a puzzle, commented upon in Ref. [16], that the production mechanism appeared not to be as expected given the anticipated hybrid dynamics. Instead of b_1–exchange, leading to the $\pi + b_1(1235)$ coupling according to rule C, significant $\pi + \rho$ coupling may be responsible. In view of Eq. 8 above, it is clear that the latter coupling may be significant on the scale of the πf_1 signal; the final state decays into $\pi + \rho$ should therefore also be investigated experimentally.

If the current BNL data are sustained, a problem emerges for decays to $\eta_u(1295)\pi$. Estimates [4] for the branching ratios to the final state $(K^+\bar{K}^0\pi^-)\pi^-$ selected by the experiment, seem to indicate a larger signal in $\eta_u(1295)\pi$ (~ 2 MeV) than in $f_1(1285)\pi$ (~ 1.5 MeV), contrary to what was observed.

CHARMONIUM HYBRIDS

The reason for interest in *charmonium* hybrids "H_c" derives from the expectation that their masses are better defined than is the case for their light quark counterparts enabling firmer predictions and, due to the smaller amount of phase space available in the corresponding decay channels, their widths are smaller.

Above the $D^{**}D$ theshold hybrids decay preferentially into $D^{**}D$ [17] according to rule C. For H_c below the $D^{**}D$ threshold the flux–tube model predicts [4] very small widths by rule B (decays into DD, $D^*\ D$ and $D^*\ D^*$ are almost forbidden). H_c is predicted to exist at 4.1 - 4.2 GeV [3, 8], above the DD, $D^*\ D$, $D^*\ D^*$ thresholds, but below the $D^{**}D$ thesholds. The dominant decays may hence be through mixing between H_c and conventional $c\bar{c}$. The simplest explanation is that these states are roughly 50 : 50 mixtures of the $c\bar{c}$ state $\psi(3S)$ existing in this mass region [18] and an "inert" H_c state. A mixing of 50% can arise naturally if there is mass degeneracy between two "primitive" states. The possibility of such a mixing between the primitive $3S$ $c\bar{c}$ at 4100 MeV and a H_c state, close by in mass, has recently been suggested [18]. If such degeneracy occurs one immediately expects that the physical eigenstates will tend to be

$$\psi_\pm \simeq \frac{1}{\sqrt{2}}(\psi(3S) \pm H_c)$$

In such an eventuality both the dominant production in e^+e^- annihilation and the prominent hadron decays will be driven by the $\psi(3S)$ component, leading to intimate relationships [18] between the properties of the two eigenstates which are then identified as $\psi(4160) \equiv \psi_+$ and $\psi(4040) \equiv \psi_-$.

These predictions may be tested at SPEAR or at a future Tau-Charm Factory. Beijing e^+e^- annihilation experiments may also soon have high enough luminosity to produce $J^{PC} = 1^{--}$ states above the DD threshold.

Bottomonium hybrids : Bottomonium hybrids are expected to be more difficult to produce than charmonium hybrids. Detection in e^+e^- annihilation of a $J^{PC} = 1^{--}$ hybrid above the BB threshold at the SLAC B-factory could be a possibility, though.

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Further reading (overviews) :

1. T. Barnes, "Signatures for Hybrids", ORNL-CCIP-93-14, RAL-93-069, in *Conf. on Exclusive Reactions at High Momentum Transfers*, Elba (1993).
2. N. Isgur, "Hadron Spectroscopy", in *Hadrons and Hadronic Matter*, ed. D. Vautherin *et al.*, Plenum Press (1990).
3. J. Paton, *Nucl. Phys.* **A446** (1985) 419; *ibid.* **A508** (1990) 377.

References

[1] R. Kokoski and N. Isgur, *Phys. Rev.* **D35** (1987) 907.

[2] T. Barnes, *Proc. of HADRON95*, Manchester (1995).

[3] T. Barnes, F.E. Close and E.S. Swanson, RAL-94-106, hep-ph/9501405.

[4] P.R. Page, *D.Phil. Thesis*, Univ. of Oxford (1995).

[5] P.R. Page, *Nucl. Phys.* **B446** (1995) 189.

[6] N. Dowrick, J. Paton and S. Perantonis, *J. Phys.* **G13** (1987) 423; S.J. Perantonis, *D. Phil. Thesis*, Univ. of Oxford (1987).

[7] F.E. Close and P.R. Page, *Nucl. Phys.* **B443** (1995) 233; *ibid.*, *Phys. Rev.* **D52** (1995) 1706.

[8] C. Michael *et al.*, *Nucl. Phys.* **B347** (1990) 854; *Phys. Lett.* **B129** (1983) 351.

[9] A. Donnachie and Yu. Kalashnikova, *Z. Phys.* **C59** (1993) 621; A.B. Clegg and A. Donnachie, *Z. Phys.* **C62** (1994) 455.

[10] VES Collaboration, A. Zaitsev, *Proc. of* 27^{th} *Int. Conf. on High Energy Physics*, Glasgow, (1994) p. 1409; VES Collaboration, D. Ryabchikov, *Proc. of HADRON95*, Manchester (1995).

[11] C. Daum *et al.* (ACCMOR Collaboration), *Nucl. Phys.* **B182** (1981) 269.

[12] D. Aston *et al.*, *Nucl. Phys.* **B189** (1981) 15;
G. Condo *et al.*, *Phys. Rev.* **D43** (1991) 2787.

[13] Y. Eisenberg *et al.* Phys. Rev. Lett. **23** 1322 (1969).

[14] A. Cooper, Ph.D. Thesis, Queen Mary and Westfield College, London University, 1994 (unpublished); Chrystal Barrel Collaboration, C. Pinder, *Proc. of HADRON95*, Manchester (1995); *ibid.* T. Degener.

[15] N. Isgur, R. Kokoski and J. Paton, *Phys. Rev. Lett.* **54** (1985) 869.

[16] J.H. Lee *et al., Phys. Lett.* **B323** (1994) 227.

[17] P.R. Page, hep-ph/9410323, *Proc. of "Quark Confinement and the Hadron Spectrum"*, 20-24 June 1994, Como, Italy.

[18] F.E. Close and P.R. Page, "Do ψ (4040), ψ (4160) signal hybrid charmonium?", OUTP-95-13P, RAL-95-035.